# Adaptive Kinetic Building Facades with Integrated Photovoltaic Systems as a Strategy for Energy Optimization in the Indian Subcontinent

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**Abstract -** This study evaluates the performance of adaptive kinetic façades integrated with photovoltaic (PV) systems as a strategy for improving renewable energy generation in India's diverse climatic conditions. Using a unified simulation workflow developed in Grasshopper and Ladybug Tools, annual energy output for 1 kW static and single-axis kinetic façade PV systems was calculated for five representative cities Delhi, Ahmedabad, Mumbai, Bengaluru, and Leh each corresponding to one of India's major climatic zones. Results indicate that kinetic tracking enhances PV generation by roughly 21% across all locations, with the most substantial absolute gains occurring in regions characterized by clear skies and strong direct solar radiation. To contextualize these findings, two real-world façade PV projects the Adaptive Solar Facade (ASF) at ETH Zürich and the Ctrl S Data Centre BIPV installation in Mumbai were examined for their operational mechanisms and climatic relevance. While kinetic systems show strong advantages in composite, hot-dry, and cold regions, static façades remain preferable in warm humid and moderate climates where diffuse radiation dominates and maintenance demands are greater. Overall, this research provides climate-responsive guidance for incorporating kinetic BIPV systems into India's rapidly expanding high-rise urban fabric.

***Key Words***: Kinetic façade, BIPV, photovoltaic systems, façade energy generation, Grasshopper, Ladybug Tools, Indian climatic zones.

## 1. INTRODUCTION

India is undergoing rapid urban transformation marked by increasing high-rise development, densely packed city center, and rising electricity consumption. This shift has placed significant pressure on conventional rooftop photovoltaic systems, which are often limited by space constraints in tall buildings and compact urban environments. As a result, vertical building envelopes traditionally passive elements are now being reconsidered as potential solar energy-producing surfaces. Studies show that even though vertical PV receives lower irradiance compared to optimally tilted rooftop systems, façade-integrated PV can still provide meaningful energy contributions, especially in regions with strong seasonal or daily solar exposure. [1]

At the same time, kinetic and adaptive façade technologies have gained momentum within architectural and engineering research. These systems are capable of modifying their physical configuration in real time through rotation, translation, or deformation to optimize daylight, heat gain, ventilation, or solar collection [2]. Their ability to dynamically respond to environmental changes makes kinetic façades promising candidates for maximizing PV output when integrated with photovoltaic modules.

**Fig -1**: The Adaptive Solar Facade (ASF) retrofitted on the HIL building at ETH Zürich.
**Source:** Research Gate

Despite this potential, India lacks comprehensive research comparing the performance of kinetic and static façade PV systems across its five distinct climatic zones. This makes it challenging for architects and engineers to determine when kinetic systems offer meaningful value relative to their increased complexity, cost, and maintenance requirements. This study responds to that need by applying consistent simulation methods across five geographically and climatically distinct Indian cities.

## 2. BACKGROUND

India's climatic diversity significantly influences solar energy potential and façade performance. Cities such as Delhi and Ahmedabad receive intense direct radiation for most of the year, making them well-suited for PV installations. Mumbai, however, experiences high humidity and frequent cloud cover, reducing the effectiveness of tracking mechanisms and exposing mechanical systems to corrosion risk. Leh, situated at high altitude, receives some of the highest solar radiation levels in the country due to low atmospheric density and clear skies.

Photovoltaic technology, when integrated into building façades (BIPV), provides dual benefits generating renewable energy while functioning as an architectural cladding system. Yet, most façade PV installations in India remain static, despite the emerging global interest in kinetic photovoltaic façades and adaptive solar technologies. This study aims to bridge this knowledge gap through quantitative climatic analysis and case study evaluation.

## 3. LITERATURE REVIEW

India's climatic diversity ranging from cold high-altitude deserts like Leh to warm–humid coastal regions such as Mumbai creates substantial variation in solar altitude, cloud cover, humidity, and atmospheric clarity, all of which directly affect the performance of façade-integrated photovoltaic systems [3]. Locations with high Direct Normal Irradiance (DNI) naturally support better energy generation, especially for systems capable of tracking the sun. Within this context, kinetic façade systems have emerged as a major area of innovation. These dynamic building skins incorporate controlled movement through mechanical actuators, pneumatic components, or responsive materials, allowing the façade to rotate or deform in response to sunlight, temperature, or user comfort requirements [2]. Their real-time adaptability enhances solar tracking, improves shading efficiency, and contributes to better indoor environmental conditions compared to static façades.

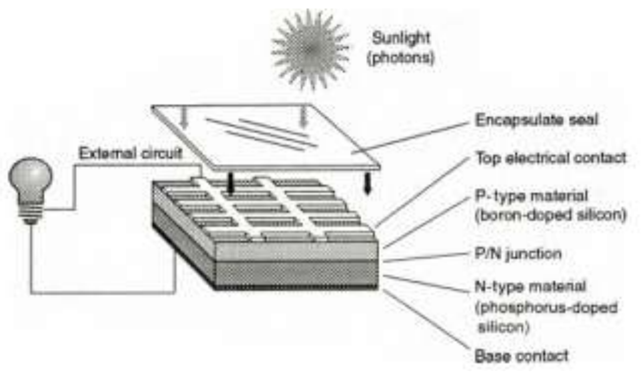


**Fig -2**: A section through a typical PV cell. Photons of light generate free electrons**.**
**Source:** Lechner, N. (2015). Heating, Cooling, Lighting: Sustainable Design Methods for Architects (4th Edition).

Building-Integrated Photovoltaics (BIPV) further expand the role of the architectural envelope by enabling it to serve as both cladding and a renewable energy generator. This dual function is especially beneficial in dense high-rise environments, where façades provide significantly more usable surface area than rooftops, and where vertical PV installations can contribute to peak-load reduction by shading interior spaces [4]. Kinetic PV façades push this idea further by combining movement with photovoltaic capability. A leading example is the Adaptive Solar Facade (ASF) from ETH Zürich, which integrates thin-film PV modules with soft robotic actuators capable of dual-axis rotation. This system automatically reorients itself based on solar position, simultaneously maximizing electricity generation and providing responsive shading, demonstrating the performance potential of motion-enabled PV surfaces [5].

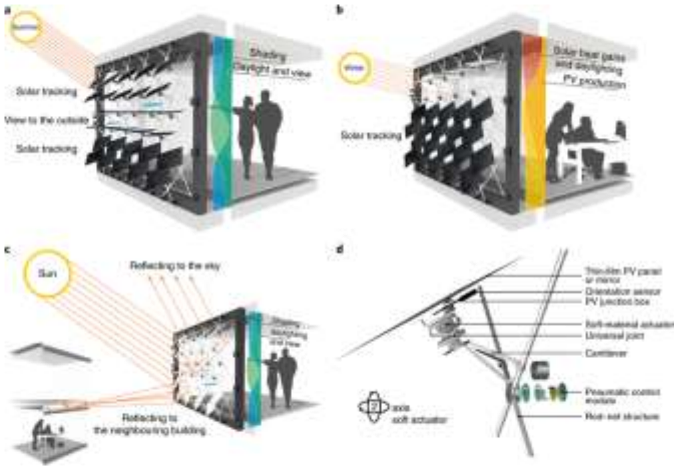


**Fig -3**: Functional Operation and Components of the Adaptive Solar Facade (ASF) System
**Source:** Research Gate

Recent literature also highlights the emergence of hybrid kinetic systems inspired by natural adaptive processes. These systems draw from biomimetic strategies such as plant movement or leaf orientation to regulate heat gain, daylight penetration, and solar harvesting. They integrate PV technologies with algorithmic control and real-time environmental sensing, creating building skins that actively respond to climatic shifts at both hourly and seasonal time scales. Together, these studies establish a strong foundation for evaluating how kinetic PV façades might perform in India's dynamic climatic contexts, where solar conditions vary significantly across regions.

## 4. METHODOLOGY

### 4.1 Need of the Study

A climate-responsive investigation of kinetic façade PV performance in India is crucial because existing global research originates largely from Europe and North America, where climatic conditions differ substantially. Indian cities face high solar variability, humidity, dust accumulation, and some of the highest cooling demands globally, making façade-integrated PV systems particularly relevant. Yet there has been no unified study comparing static and kinetic façade PV performance using identical system parameters across India's major climatic zones. Without this data, building professionals lack evidence-based criteria for selecting façade energy systems. This study provides the missing technical foundation necessary for climate-appropriate design decision-making.

### 4.2 Tools and Stimulation Setup

The simulations were carried out using Grasshopper**,** a visual programming interface within Rhinoceros 3D. A trial version of Rhino 7 was used during the modelling and prototype development process. To ensure consistency and comparability, two separate façade prototypes one static and one kinetic were created in Grasshopper. Both prototypes used identical module dimensions, façade orientation, and PV efficiency so that only movement behaviour differed.

For solar and energy analysis, the Ladybug Tools plugin was used. Hourly climate data was imported using EPW files obtained from the official Ladybug EPW Map database (https://www.ladybug.tools/epwmap/). The Ladybug "Photovoltaics Surface" component was used to calculate annual electricity generation based on incident irradiation, PV module efficiency, and façade tilt/rotation inputs.

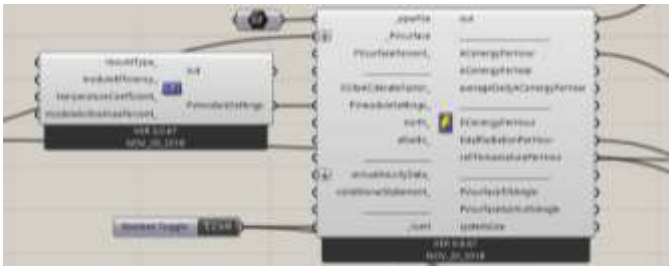

**Fig -4**: Ladybug Photovoltaics Surface component used for calculating annual PV energy output from the static and kinetic façade prototypes.
**Source:** Author

The static prototype used a fixed tilt equal to the latitude of each city, while the kinetic prototype was assigned a single-axis east–west rotation that updates panel orientation hourly based on sun-path data. Ladybug computed total annual PV output from both prototypes, ensuring identical simulation conditions across all five cities. This integrated workflow allowed high accuracy in comparing static and kinetic performance.

## 5. DATA COLLECTION

Energy simulation for this study was performed using the Ladybug Photovoltaics Surface component, which computes PV output from hourly solar radiation data and user-defined geometric parameters. A prototype of the façade module was created in Grasshopper for both static and kinetic variants. The static version maintained a constant tilt defined by the city's latitude, whereas the kinetic version incorporated a rotational hinge allowing east–west tracking aligned with hourly sun vectors.

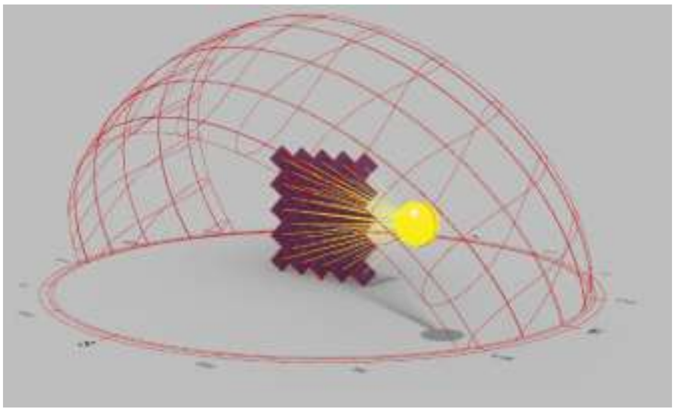

**Fig -5**: façade prototype aligned with the 9:00 AM sun position within the solar path dome.
**Source:** Author

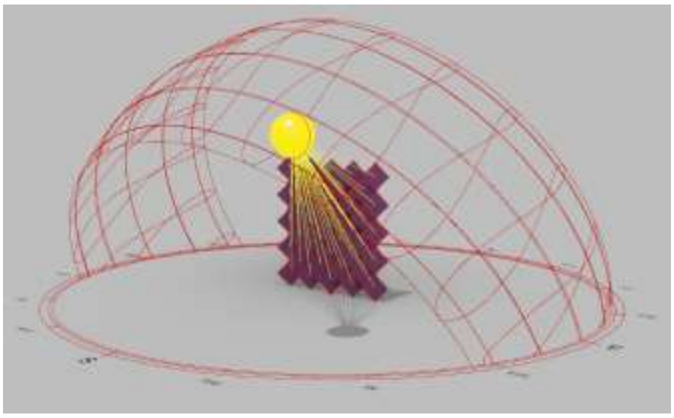

**Fig -6**: façade prototype aligned with the 11:00 AM sun position within the solar path dome.
**Source:** Author

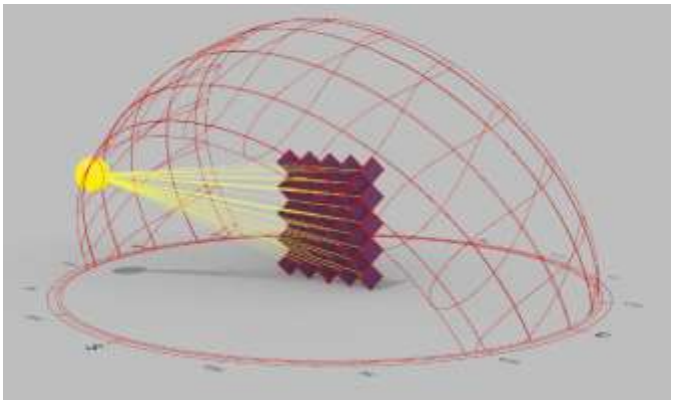

**Fig 7**: façade prototype aligned with the 4:00 PM sun position within the solar path dome.
**Source:** Author

EPW climate files for Delhi, Ahmedabad, Mumbai, Bengaluru, and Leh were downloaded from the Ladybug EPW Map database, ensuring certified and uniform weather data inputs. Each façade prototype was linked directly to irradiation data through Ladybug, allowing the model to generate annual PV electricity output (kWh/year).

The results are summarized in Table 1, reflecting the combined performance of static and kinetic systems and enabling climate-specific comparisons of façade PV yield.

| S. NO. | CITY | CLIMATE | LATITUDE | TILT | STATIC (kWh/yr) | KINETIC (kWh/yr) | GAIN (%) |
|---|---|---|---|---|---|---|---|
| 1 | Leh | Cold | ~34.1° N | 34° | 1982 | 2405 | 21.30% |
| 2 | Delhi | Composite | ~28.7° N | 29° | 1511 | 1833 | 21.30% |
| 3 | Ahmedabad | Hot-Dry | ~23.0° N | 23° | 1492 | 1808 | 21.20% |
| 4 | Bengaluru | Moderate | ~12.9° N | 13° | 1395 | 1692 | 21.30% |
| 5 | Mumbai | Warm-Humid | ~19.0° N | 19° | 1343 | 1628 | 21.20% |

**Table -1**: The combined static and kinetic PV outputs for a 1 kW façade system across the five climatic zones.
**Source:** Author

## 6. CASE STUDIES

### 6.1. Adaptive Solar Facade (ASF), ETH Zürich

The Adaptive Solar Facade (ASF) developed at ETH Zürich is one of the most advanced examples of a kinetic building envelope integrating photovoltaic modules. It demonstrates how actuation, automation, and solar tracking can be merged into a compact façade unit capable of generating energy while improving indoor comfort. [5]

#### 6.1.1. How ASF Works

The ASF consists of lightweight thin-film PV panels mounted on soft robotic pneumatic actuators. Each module can rotate independently along two axes, allowing it to adapt to changing sun angles throughout the day and across seasons. The system optimizes both solar exposure for electricity generation and shading to maintain indoor thermal comfort. Its high spatial resolution of movement enables nuanced façade responses, including glare control, daylight redirection, and solar tracking.

#### 6.1.2. Role in this Study

The ASF served as the conceptual foundation for understanding how kinetic PV façades behave in real-world conditions. Its documented performance helped validate the simulation assumption that kinetic tracking can enhance PV output by approximately 20–25%, which closely aligns with the 21% improvement observed across Indian climates in this study. The ASF also provided insight into actuator behaviour, control logic, and the dual-function nature of kinetic PV systems key considerations when evaluating their suitability for Indian climates. [5]

**Fig -8**: Adaptive Solar Façade, ETH Zurich
**Source:** Architecture and Building Systems

### 6.2. Ctrl S Data Centre, Mumbai (Vertical BIPV Façade)

The Ctrl S Data Centre in Mumbai houses India's largest vertical façade-integrated PV system, representing one of the country's most significant real-world BIPV applications in a dense urban context. Its scale, architectural integration, and climatic location make it an excellent benchmark for assessing BIPV performance under warm-humid conditions. [6]

#### 6.2.2. How the System Works

The façade employs 863 kWp of mono-crystalline PV modules installed within a ventilated rainscreen cladding system. Panels cover all four major orientations north-east, north-west, south-east, and south-west allowing energy production throughout the day. The system generates approximately 593 MWh per year, all of which is used internally by the data centre, demonstrating the viability of vertical PV integration even when roof space is constrained. The rainscreen assembly improves thermal performance while protecting the modules from moisture a crucial factor in humid climates like Mumbai.

#### 6.2.3. Role in This Study

The Ctrl S façade provided a real-world example validating the simulation results for Mumbai, which consistently showed the lowest PV output among the five cities due to diffuse radiation dominance. The operational experience of Ctrl S particularly the reduced energy yield and increased maintenance needs in a humid climate directly supports the study's conclusion that kinetic systems are less suitable for such environments. This case reinforces the importance of selecting façade strategies based on climate.

**Fig -9**: Ctrl S Data Centre, Mumbai
**Source:** Energetica India

# 7. ANALYSIS AND INFERENCE

### 7.1. Static Façade Performance

Static façades performed best in climates with strong direct radiation. Leh showed the highest output due to its clear skies, high altitude, and low humidity. Delhi and Ahmedabad also produced strong results because of long sunshine hours and favourable solar angles. In contrast, Mumbai and Bengaluru recorded lower performance as diffuse radiation dominates in humid and moderate climates.

### 7.2. Kinetic Benefits

Kinetic façades demonstrated a consistent performance improvement of ~21% across all climates. The ability to rotate and follow the sun helped maintain better incident angles, increasing annual energy yield. The largest absolute gains occurred in Leh, Delhi, and Ahmedabad, where clear sky conditions allowed tracking to capture significantly more direct radiation. Even in diffuse climates, kinetic systems still provided modest but measurable improvements.

### 7.3. Suitability of Kinetic Systems

The suitability of kinetic systems in India depends largely on climate, maintenance constraints, and expected energy gains. In cold, composite, and hot–dry climates, the availability of strong direct normal irradiance (DNI) makes kinetic tracking highly advantageous. Clear skies allow tracking mechanisms to substantially outperform static systems because module orientation can closely follow the sun's path. Regions like Leh, Delhi, and Ahmedabad therefore justify the additional mechanical complexity due to higher absolute energy gains.

In contrast, warm-humid climates such as Mumbai experience heavy cloud cover, high humidity, and significant diffuse radiation. These conditions reduce the benefit of tracking since the sun is often obscured, leading to only marginal improvements over static systems. Humidity also accelerates wear on actuators and mechanical components, increasing long-term maintenance costs. Moderate climates like Bengaluru offer stable but less intense solar radiation, making the energy gains insufficient to justify kinetic systems in most cases. Consequently, static BIPV remains the more robust and cost-effective choice for humid or moderate regions.

### 7.4. Overall Insight

The results show that while kinetic façades outperform static systems everywhere, their true value depends on climate. In high-DNI regions cold, composite, and hot-dry the energy gain justifies the added mechanical complexity. In warm-humid and moderate climates, the improvement is smaller and maintenance challenges are higher, making static façades more practical. A climate responsive approach ensures optimal façade PV selection.

# 7. CONCLUSION AND FUTURE SCOPE

This study demonstrates that adaptive kinetic BIPV façades provide meaningful improvements in solar energy generation across India's varied climatic regions, particularly in cold, composite, and hot–dry climates where direct solar radiation is abundant. Although kinetic systems consistently outperform static ones in relative terms, their practical feasibility varies by climate due to differing maintenance requirements and environmental stresses. As Indian cities continue to densify, façade-based PV systems especially kinetic ones in suitable climates can play a vital role in sustainable energy generation. Future research should examine the economic viability of kinetic façades, explore corrosion-resistant actuation technologies for humid regions, and develop integrated PV-shading hybrid systems tailored to India's climate. Additionally, incorporating kinetic façade strategies into India's ECBC and IGBC guidelines will support broader adoption of adaptive solar technologies.

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